



Binding of quasi two-dimensional biexcitons

Birkedal, Dan; Singh, J; Vadim, Lyssenko; Hvam, Jørn Märcher

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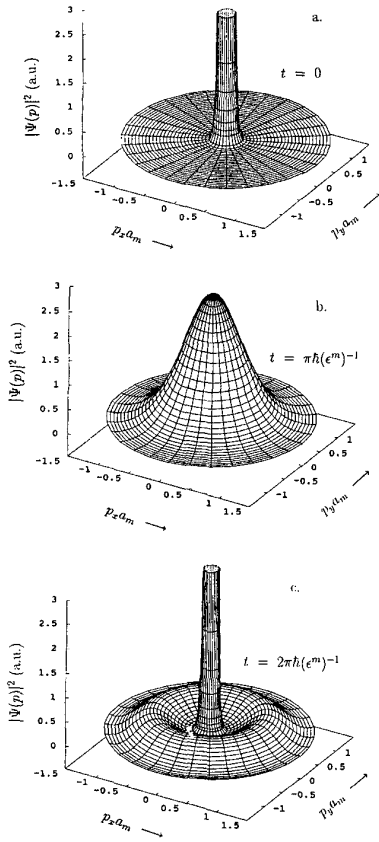
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JThJ3 Fig. 1 Transient evolution in momentum space of the wave function $\Psi(p)$ of two correlated quasi-2D excitons initially excited by an ultrashort femtosecond optical pulse ($\tau_{\text{pulse}} \ll \hbar/\epsilon^m$); $t = 0$ (a), $t = \pi\hbar/\epsilon^m$ (b), and $t = 2\pi\hbar/\epsilon^m$ (c).

oscillations back and forth in 2D momentum space can be interpreted as quantum beats of the two x 's resulting from the Coulombic attraction, which causes a change of the relative momentum p up to the values $\sim 1/a_m$. Complicated quantum interference given by Eq. (1) destroys the oscillations within a few periods. The transient coherent stage of PL explains the finite rise-time of PL and allows to estimate the m binding energy straightforwardly by $\epsilon^m \approx \pi\hbar/\tau$, where τ is the time of the (first) maximum of the PL signal.

The recently developed bipolariton model² is adopted to analyze the coherent stage of PL. We conclude that the main "hidden" channel of the m decay is dissociation into two outgoing surface polaritons rather than an observable decay into bulk radiative modes. A spatial anisotropy of transient PL is also analyzed.

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QThJ4

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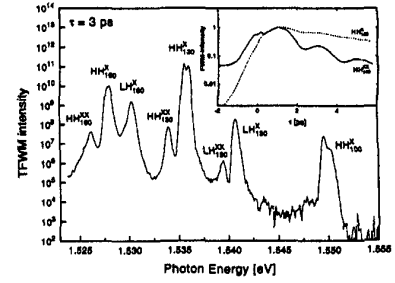
Binding of quasi two-dimensional biexcitons

D. Birkedal, J. Singh, V. G. Lyssenko, J. M. Hvam, Mikroelektronik Centret, The Technical University of Denmark, DK-2800 Lyngby, Denmark

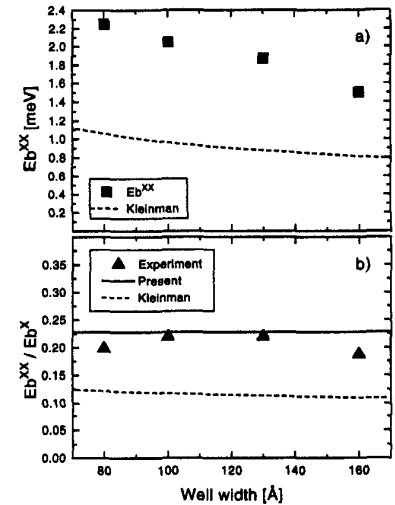
In this presentation we report on a determination of the biexciton binding energies in GaAs/AlGaAs quantum wells of different widths and the results of a theoretical calculation of the ratio of the biexciton binding energy E_b^{xx} to that of the exciton E_x^x . We determine the binding energies using spectrally resolved transient four-wave mixing (TFWM) and photoluminescence (PL). One single structure was grown by MBE, containing 10 wells of each of the thicknesses 80, 100, 130, and 160 Å, separated by 150-Å $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barriers. For the TFWM experiments, the sample was excited by 100-fs pulses from a self modelocked Ti:sapphire laser in the two-beam self-diffraction geometry.¹ The PL was either excited by a continuous wave HeNe laser or by the Ti:sapphire laser. The sample was kept at 5 K during the experiments.

The PL experiments with the HeNe laser resulted in PL peaks for the heavy hole excitons (HH^x) and biexcitons (HH^{xx}). The biexciton PL-peaks could be fitted accurately by use of a lineshape suggested by Phillips *et al.*,² and the intensity was observed to increase super-linearly with excitation power. With the laser resonant at the heavy hole exciton of the 130 Å well, HH_{130}^x , the TFWM spectrum is shown in Fig. 1 for a delay of 3 ps. Distinct lines are observed for all the exciton resonances. Below the exciton resonances, lines are seen that coincide with the lines observed in the luminescence. They are identified as being TFWM signals resulting from two-photon transitions to the biexciton states via the intermediate exciton states. By appropriate tuning of the laser, we obtain the response from the HH^{xx} in each of the quantum wells and determine their binding energies. The well width dependence of the HH^{xx} binding energies is shown in Fig. 2a. Also shown, as a dashed curve, is the calculation by Kleinman.³

Assuming a square structure for a 2D biexciton, with two electrons and two holes separated by diagonals, $2r$, we have calculated the ratio of the binding energy of biexcitons to that of excitons analytically using the fractional dimension approach.⁴ Our model structure helps reducing the biexciton Hamiltonian into an exciton Hamiltonian with a modified reduced mass $\mu_{xx} = 2/3\mu_x$ and modified dielectric constant $\epsilon_{xx} = \sqrt{2/4} - \sqrt{2}\epsilon_x$, where μ_x and ϵ_x are the reduced effective mass and dielectric constant of the material, respectively. The biexciton binding energy is thus derived as a function of the exciton binding energy:



QThJ4 Fig. 1 Spectrally resolved four-wave mixing at $\tau = 3$ ps showing the heavy hole and light hole biexcitons. The inset shows quantum beats in the four-wave-mixing intensity of the heavy hole exciton and biexciton as a function of delay.



QThJ4 Fig. 2 Well width dependence of binding energies. (a) Heavy hole binding energies, and (b) ratio of the heavy hole biexciton to exciton binding energy. The dashed curves in (a) and (b) indicate the calculation of Kleinman,³ the full curve in (b) shows the result of the present calculation, and the markers indicate the experimental data.

$$E_b^{xx} = \left[\frac{\mu_{xx}}{\mu_x} \frac{\epsilon_x^2}{\epsilon_{xx}} - 2 \right] E_x^x, \quad (1)$$

which gives $E_b^{xx}/E_x^x \approx 0.228$, independently of the fractional dimension and hence the well width.

The binding energies of the heavy hole excitons have been estimated from photoluminescence excitation measurements. In Fig. 2b we have compared the experimental ratio of the heavy hole biexciton binding energy and the heavy hole exciton binding energy E_b^{xx}/E_x^x with those of Kleinman³ and the present calculation. The experimental results deviate significantly from the calculation by Kleinman but agree quite well with our calculation.

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Kinetics of a nearly degenerate gas of excitons in Cu₂O

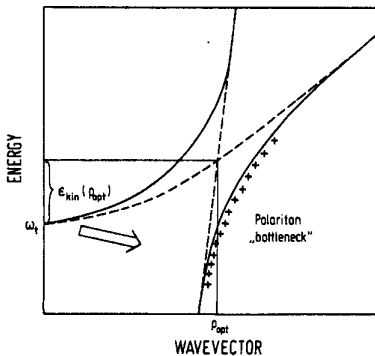
A. L. Ivanov, C. Ell, H. Haug, *Institut für Theoretische Physik, J. W. Goethe-Universität Frankfurt, Robert-Mayer-Str. 8, Postfach 11 19 32, D-60054 Frankfurt am Main, Germany*

The relaxation of a degenerate gas of excitons (x 's) coupled to an LA-phonon bath toward Bose-Einstein condensation (BEC) is analyzed within the kinetic equations. The optical processes, *i.e.*, the radiative decay and the polariton effect, are included explicitly.

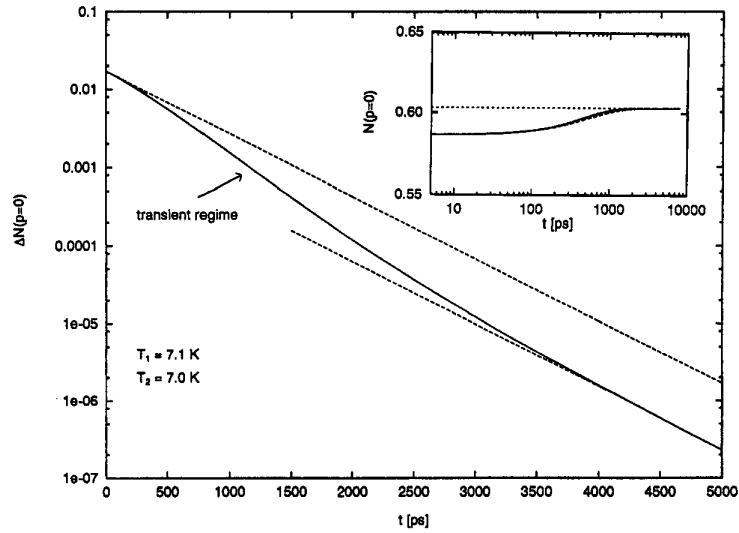
The observation of high quantum degeneracy and the asymptotic approach of BEC have been reported for a Bose gas of ortho- x 's in Cu₂O.¹ In these experiments, both the resonant and LO-phonon assisted ortho- x recombinations give an observable optical signal. However, the radiative renormalizations of the ortho- x dispersion strongly influence the relaxation kinetics. Recent experiments clearly demonstrate a well-developed polariton effect for the quadrupole-allowed ortho- x 's in Cu₂O at $T = 2$ K.² The corresponding polariton coupling is given by $\Omega_c(p) = (\hbar^2 p^2 / \epsilon_x)^{1/2}$, where $\epsilon_x = 6.5$, $f = 3.7 \times 10^{-5}$, and p is the polariton wave vector. The anomalously weak ortho- x 's - LA-phonon interaction in Cu₂O does not destroy the polariton effect.¹

Quasi-equilibrium BEC may coexist with the polariton effect under the following criterion:

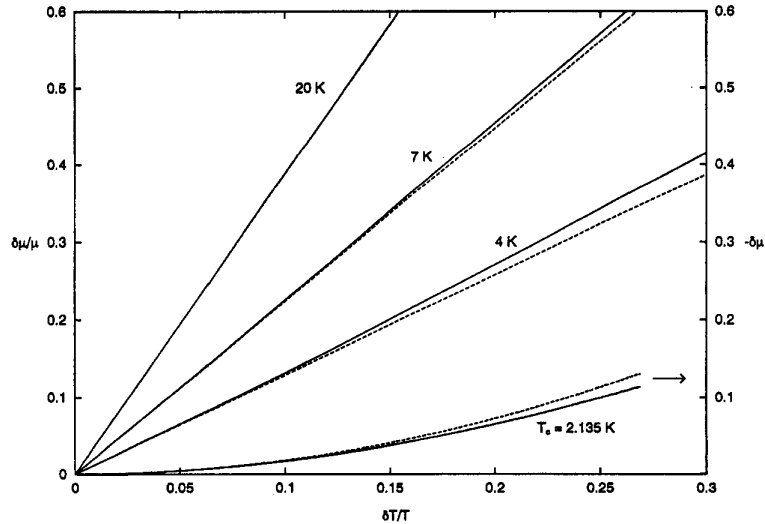
$$\epsilon_{kin}(p_{opt}) = \frac{\hbar^2 p_{opt}^2}{2M_x} \gg \Omega_c(p_{opt}), \quad (1)$$



QThJ5 Fig. 1 Schematic of the effective scattering of the ortho- x 's from state $p = 0$ of the upper polariton branch to the polariton bottleneck region of the lower polariton branch.



QThJ5 Fig. 2 Dynamics of population at $p = 0$ in the adiabatic cooling from $T_1 = T + \Delta T = 7.1$ K to $T_2 = T = 7.0$ K of the nearly degenerate gas ($T_c = 2.135$ K) of para- x 's. Solid lines = numerical simulations within the kinetic equations; dashed lines = analytical approximations.



QThJ5 Fig. 3 Approximations for the thermodynamic relationships of an ideal Bose gas of particles with quadratic dispersion. Solid lines = exact results; dashed lines = approximations.

where k_{opt} is the wave vector of the resonant x -photon transition and M_x is the x mass (see Fig. 1). For ortho- x 's this condition is broken because $\epsilon_{kin}(p_{opt}) \approx 9.7$ μ eV and $\Omega_c(p_{opt}) \approx 123.7$ μ eV. In this case, the ortho- x 's relax to the bottleneck region of the lower polariton branch rather than accumulate at state $p = 0$ of the upper polariton branch. Our numerical simulations clearly demonstrate such a relaxation kinetics, explain the low-energy tail in phonon-assisted ortho- x 's recombination, and show an unusual relaxation kinetics along the lower polariton branch.

We conclude that the quantum degeneracy is high both for the high-energy tail of the distribution function (chemical po-

tential $\mu_{eff} \rightarrow 0$) and within the bottleneck region, but the quasi-equilibrium BEC at $p = 0$ cannot develop for ortho- x 's in Cu₂O.

The polariton effect is absent for the para- x 's. Therefore we analyze the relaxation kinetics within the standard kinetic equations for Bose particles with quadratic dispersion. For $T \gg T_c$, the adiabatic cooling of the quasi-equilibrium x 's gas from $T + \Delta T$ to T is exponential: $\delta T = \Delta T \exp[-t/\tau_{eff}^{(1)}]$ (see Fig. 2). However, the kinetics slows down considerably if $T \rightarrow T_c$. In this case, $\delta T = \Delta T/[1 + t/\tau_{eff}^{(2)}]$. The number of condensed x 's at state $p = 0$ grows very slowly $\propto [1 + t/\tau_{eff}^{(2)}]^2$. This nonexponential kinetics implies that a